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TITLE: Subharmonic Imaging and Pressure Estimation for  
Monitoring Neoadjuvant Chemotherapy

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## 4 INTRODUCTION

In the United States, close to 5 – 20 % of newly diagnosed breast cancer and 10 – 30% of all primary breast cancer is diagnosed as locally advanced breast cancer (LABC) [1, 2]. Neoadjuvant chemotherapy (systemic preoperative chemotherapy) is currently the standard of care for LABC [3, 4]. When compared with adjuvant chemotherapy (postoperative therapy), neoadjuvant chemotherapy yields similar results for both overall survival (70% for both) and disease-free survival (53% adjuvant, 55% neoadjuvant) [5]. Thus, the postponement of surgery does not affect the outcome of the treatment [5, 6]. In addition, neoadjuvant chemotherapy offers considerable benefits to the patient as the treatment can shrink the tumor and even in some cases offer complete pathologic response [3, 7]. This reduction in tumor size increases the possibility of breast conservation [3, 5-7]. Maximizing the conservation of breast tissue can be of great personal importance for the self-esteem and quality of living of the patient [6]. Neoadjuvant chemotherapy can also offer an early indication of the patient's response to chemotherapy. Consequently, monitoring tumor response to neoadjuvant therapy gives the possibility of adjusting the treatment if the patient is responding poorly or not at all resulting in substantial advantages for the patient [3, 6]. This project aims at establishing noninvasive monitoring of neoadjuvant chemotherapy in the breast using subharmonic aided pressure estimation (SHAPE; U.S. Patent 6,302,845).

Generally interstitial fluid pressure (IFP) is 10-30 mmHg higher in cancerous tissue than in normal tissue although values of up to 60 mmHg have been recorded [8, 9]. Similarly, IFP in breast cancer tumors has been shown to be higher than that of surrounding breast tissue [9]. This increase is believed to be due to vascularity, fibrosis and difference in the interstitial matrix in tumors and it can result in poor transport of therapeutic drugs to tumors [8]. Taghian et al. used a wick-in-needle technique to monitor the IFP of breast cancer before and after neoadjuvant chemotherapy with two drugs used consecutively [10]. When used as a first drug Paclitaxel decreased the IFP by 36% ( $p=0.02$ ) whereas with Doxorubicin as a first drug there was only 8% reduction ( $p=0.41$ ). As this was a hypothesis-generating study they did not show any outcome related to the relationship between IFP and therapy response [10]. However, the level of IFP has been shown to predict disease free survival for cervix cancer (34% disease free survival (DFS) if  $IFP > 19$  mmHg, 68% DFS if  $IFP < 19$  mmHg ( $p = 0.002$ )) [11]. Thus, the level of interstitial fluid pressure (IFP) in breast cancer tumors could potentially be used to monitor the response to neoadjuvant chemotherapy.

Contrast agents have been used for two decades to improve visualization in ultrasound (US) imaging as they enhance the difference in reflectivity between tissues [12]. Because of the difference in compressibility between the medium and the microbubble any changes in pressure induce changes in the size of the microbubble [13]. This in turn affects the reflectivity and resonant frequency of the bubble [13, 14]. In subharmonic imaging (SHI) pulses are transmitted at a frequency  $f_0$  and the echoes are received at half that frequency  $f_0/2$ . SHI has been showed to be a feasible option for contrast enhanced imaging due to subharmonic generation by contrast agents and limited subharmonic generation in tissues [15]. Our group came up with a novel technique, SHAPE, utilizing

microbubbles and the subharmonic amplitude of the scattered signal [13]. We showed that there is a linear relationship between the hydrostatic pressure and the subharmonic amplitude. We propose the use of SHAPE to monitor treatment response by noninvasively measuring the IFP in breast tumors. This offers several benefits to the patient. As opposed to the wick-in-needle technique SHAPE is noninvasive and does not inflict pain. Furthermore, it allows for an early indication of responders vs. non-responders and thereby makes adjustments to therapy easier. Moreover, SHAPE has been shown to have a favorable signal-to-noise ratio so the subharmonic amplitude is not affected by background noise [13].

The SHAPE algorithm will be implemented on a state-of-the-art ultrasound scanner (Logiq 9, GE Healthcare, Milwaukee, WI) for *in vivo* monitoring of angiogenesis and IFP. This implementation will be tested with the 4D10L 3D probe and optimized *in vivo* (in canines) with the contrast agent Definity. The ability of SHI to depict macro- and micro-vascularity (the latter as a model for tumor angiogenesis) will also be assessed. Finally, the ability of 3D SHI and SHAPE to monitor neoadjuvant chemotherapy in women with LABC (i.e., the ability to track changes in tumor angiogenesis and IFP, respectively) will be evaluated in a first in humans clinical trial. We plan to recruit 10 – 25 subjects per year who will be studied with contrast US (SHI and SHAPE) before as well as after the 1<sup>st</sup>, 3<sup>rd</sup> and last chemotherapy cycle. All subjects will also receive an MRI as part of their standard of care (before and after completion of the chemotherapy), and these results together with pathology will be compared to the 3D SHI and SHAPE studies (independently as well as combined) as a means for treatment monitoring.

Our group has proposed that SHAPE and contrast enhanced US imaging can be used to measure the IFP in LABC tumors, thus, making it possible to noninvasively monitor the tumor response to neoadjuvant chemotherapy. This method would be a considerable improvement from the wick-in-needle technique currently used for IFP measurements in LABC and allow for individualized treatments options.

## **5 BODY**

The hypothesis of this project is that IFP in breast tumors can be measured noninvasively using SHAPE and contrast enhanced US thus improving the monitoring of neoadjuvant chemotherapy. First 3D SHI and SHAPE will be implemented on a commercial scanner. The scanner will be used to monitor neoadjuvant chemotherapy in women with LABC in a first in humans clinical trial. We plan to recruit 20 – 50 subjects who will be studied with contrast SHI and SHAPE before as well as after the 1<sup>st</sup>, 3<sup>rd</sup> and last chemotherapy cycle. The specific tasks of the project (as presented in the original Statement of Work) can be found in Appendix I.

First an outline of the methods applied will be given followed by a presentation of the results to date. Finally, the conclusions and future directions of the research will be discussed.

## 5.1 Methods

Obtaining regulatory approval for the human subjects components of this proposal has been problematic. We submitted our human pilot study protocol to Lantheus Medical Imaging (for access to the ultrasound contrast agent Definity) on December 6<sup>th</sup>, 2012. Next, we prepared an amendment to our existing IND application (#112,241) with the Food and Drug Administration (FDA), which was approved by the FDA without comments on March 25<sup>th</sup>, 2013. While the FDA were reviewing our protocol, we prepared the required documentation for the TJU human subjects' approval and, as described in last year's report, final TJU approval was received on June 6<sup>th</sup>, 2013. Then we prepared documentation to be in compliance with the USAMRMC human subjects' protection requirements under the Office of Research Protections (ORP). The ORP provides human subjects protection review and compliance oversight under the Human Research Protections Office (HRPO), which received our submission on June 17<sup>th</sup>, 2013. After having received several ORP HRPO reviews and made the appropriate amendments (which also had to be approved by the TJU IRB), we were granted approval by the ORP HRPO on December 6<sup>th</sup>, 2013.

Unfortunately, Lantheus Medical underwent major financial turmoil during 2013, which resulted in most senior staff being replaced. This in turn required us to resubmit our proposal and all associated documentation for re-evaluation. The assessment at Lantheus lasted another 4 months, before we received final approval and had the contrast signed on April 23<sup>rd</sup>, 2014.

Given the delay caused by the efforts required to obtain regulatory approval for the human clinical trial, the project is approximately 12 months behind schedule and we, therefore, requested a one year no cost extension to complete the SOW (Appendix I). This extension was granted on October 16<sup>th</sup>, 2014.

### *In vivo human clinical trial*

Our group has worked in partnership with GE to perform 3D SHAPE on a state-of-the-art commercial scanner Logiq 9 with a mechanical 3D linear array (4D10L). Software to automatically optimize the acoustic output power for SHAPE [16] has also been implemented on this scanner. Our clinical trial of SHAPE with Definity for noninvasive evaluation of the IFP in breast lesions during neoadjuvant chemotherapy started in May of 2014.

Briefly, the protocol evaluates the ability of 3D SHI and SHAPE to track changes in LABC angiogenesis and IFP, respectively, by studying women undergoing neoadjuvant chemotherapy before as well as with around 10% and 60% of the neoadjuvant chemotherapy treatment delivered and after completion of the neoadjuvant chemotherapy treatment. Results will be compared to MRI and pathology. The modified Logiq 9 scanner will be used to acquire conventional and SHI images (at a transmit frequency of 5.8 MHz with the subharmonic obtained at 2.9 MHz). Using this setup, acoustic pressure amplitudes will all be below 1.5 MPa peak negative pressure, 2.5 MPa peak positive pressure ( $MI < 0.33$ ).

A baseline US grayscale scan will be used to identify the mass or abnormal area seen by mammography (or another concomitant imaging mode, such as US or MRI) and to evaluate the following criteria: diagnosis; size, shape, and orientation of the lesion; echogenicity compared to surrounding tissue. Standard Power Doppler (PDI) of the lesion or target area will also be performed. The distribution of color signals and the overall color content of the lesion will be evaluated by comparing the pattern and amount of color to the normal surrounding breast. Irregularity of the course of the vessels and anastomoses will be evaluated. Digital clips of the two baseline imaging modes will be acquired

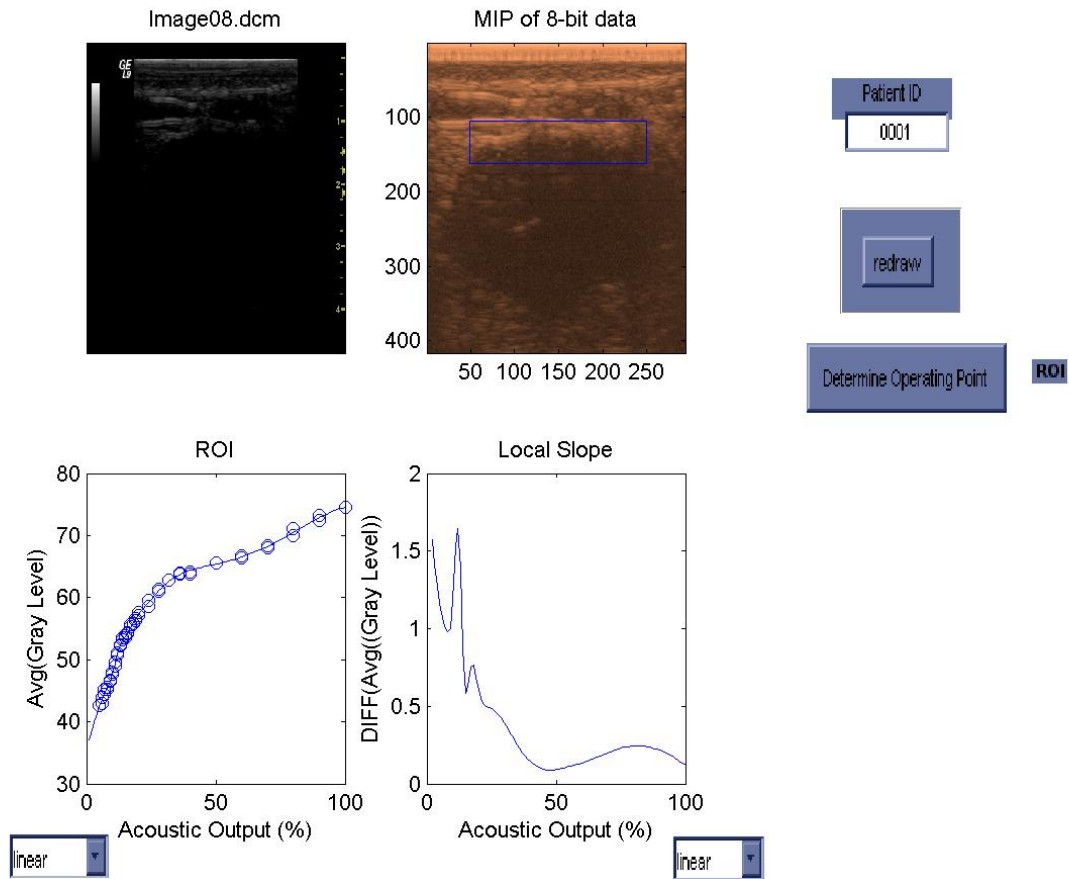
The contrast administration will be an intravenous infusion of 2 vials of Definity/50ml saline through a peripheral vein with infusion rates of 4 to 10 ml/min (titrated to effect). Next, we will run a power optimization algorithm to establish the individualized acoustic parameter settings for the case (on the first imaging study only). We will use those parameters for all subsequent imaging studies to sweep the area of the LABC to acquire 3D, pulse inversion SHI grayscale volume data. The digital clips and RF data obtained from each 3D SHI injection will be transferred to a PC for off-line analysis. The SHI images will be qualitatively analyzed as described above and compared to clinical outcomes.

## **5.2 Results and Discussion**

To date, 4 subjects have been enrolled in our pilot study. Out of those 4 subjects, one has completed all 4 3D SHI scans (i.e., she has finished the study), one subject has completed 3 out of 4 scans and one has completed 1 out of 4 scans. The last subject included in our current total of 4 was enrolled, but due to insurance issues her neoadjuvant chemotherapy treatment was delayed for almost two weeks and in that time period she changed her mind about participating in the study.

An example of the SHI images obtained for the first subject and converted into maximum intensity projection (MIP) mode (as part of the optimization algorithm) can be seen in Figure 1. The corresponding curve showing the change in subharmonic amplitude as a function of acoustic power is also shown in Figure 1 (bottom), and it can be seen that the steepest slope (i.e., the greatest SHAPE sensitivity) corresponds to an acoustic output power of 12 %. In Figure 2, the time course of the LABC treated to completion is presented. This lesion reduced in size from 2.82 x 2.22 cm to 1.04 x 0.98 cm over 15 weeks of treatment.

While the RF data processing of the studies completed to date (i.e., the IFP estimation) is still ongoing, it is clear that marked subharmonic enhancement can be seen; even at the lower acoustic output powers associated with SHAPE (Figure 3). The Logiq 9 scanner used in this project displays the 3D SHI volumes in a 2 x 2 grid representing the 3D reconstruction (lower right) as well as three orthogonal planes (sagittal, transverse and coronal). In Figure 3, the contrast enhancement can clearly be seen in the transverse and coronal planes. These efforts represent the commencement of task 3.

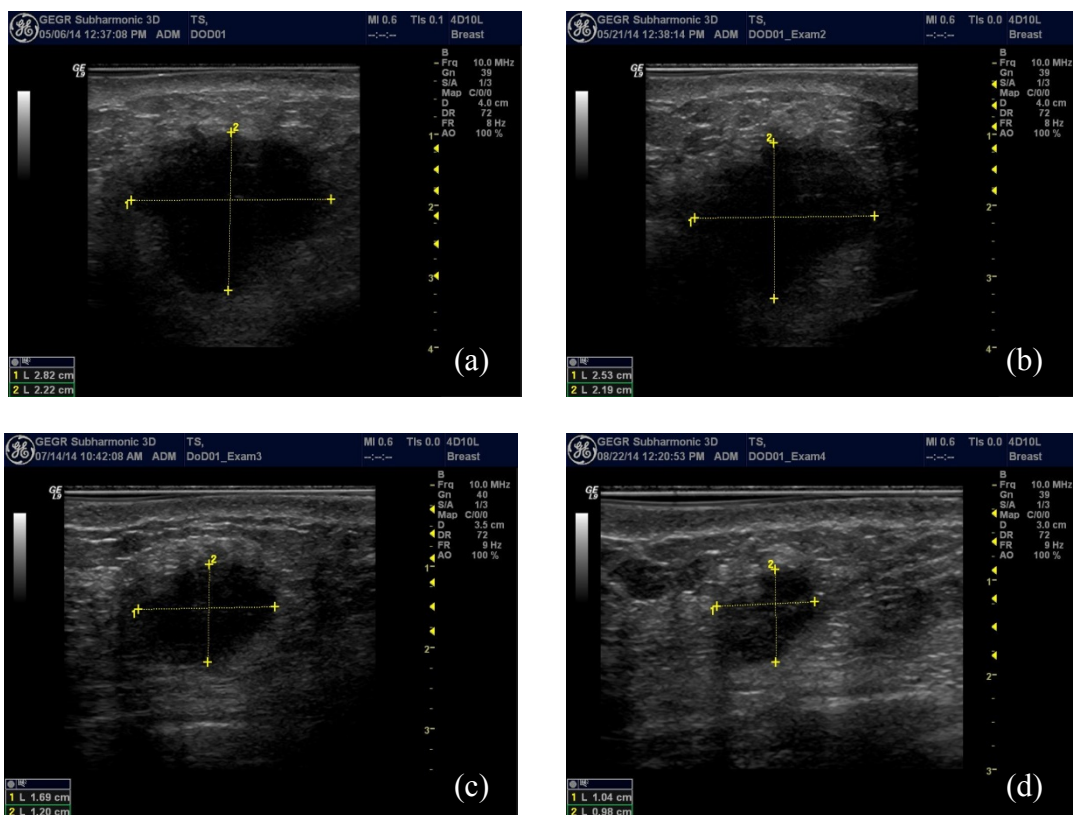


**Figure 1.** Subharmonic data from a human LABC (top left) with an ROI marked (in blue) over the anterior portion of the tumor showing contrast enhancement in MIP mode (top right). The average grayscale levels within the ROI and the local slope are also displayed (bottom) showing that 12 % acoustic output power is optimal for SHAPE in this subject.

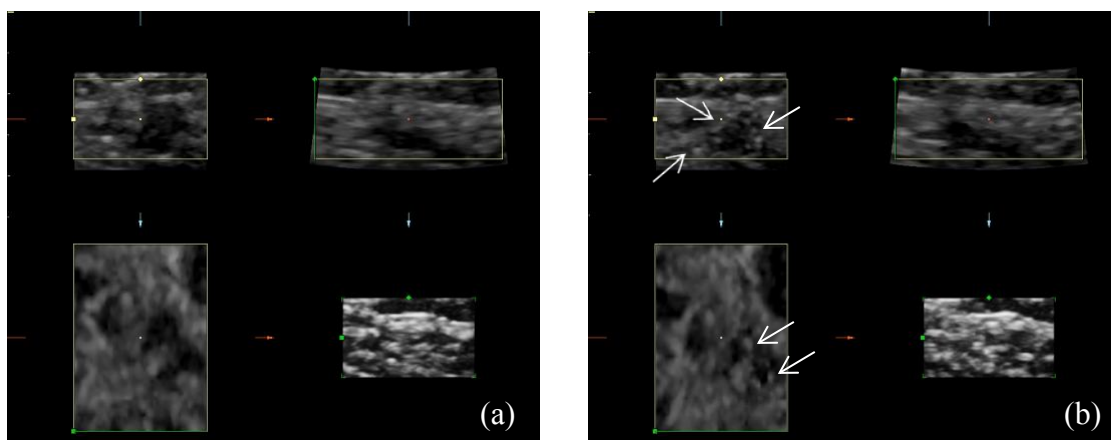
## 6 KEY RESEARCH ACCOMPLISHMENTS

- The regulatory requirements for conducting this clinical trial are finally complete.
- The *in vivo* SHAPE pilot study for monitoring neoadjuvant chemotherapy with Definity using the Logiq 9 scanner and the 4D10L probe has started.
- To date 4 patients have been enrolled (these cases include one completed, one ongoing, one partially completed and one never started).





**Figure 2.** The size of the breast cancer in this subject is seen to shrink dramatically during the time of neoadjuvant chemotherapy (about 15 weeks). Pre scan (a), after 10 % of treatment was administrated (b), after 60 % was administrated (c) and after treatment completion (d).



**Figure 3.** 4D SHI before (a) and after contrast administration (b), showing the 3D reconstruction (bottom right) as well as three orthogonal planes. Enhancement can clearly be seen in the transverse and coronal planes (arrows).

## 7 REPORTABLE OUTCOMES

### *Publications*

F. Forsberg. Subharmonic pressure measurements in human clinical trials. *J Ultrasound Med*, vol 33, pp. S45-S46, 2014.

F. Forsberg. Subharmonic imaging and pressure estimation: pre-clinical and clinical experiences. *Proc CCUM 2014*, pp. 1-10, 2014.

V. G. Halldorsdottir, A. Marshall, J. K. Dave, A. I. Forsberg, P. Machado, T. B. Fox, J. B. Liu, F. Forsberg. Subharmonic pressure estimation in breast tumors: an *in vivo* calibration study. Submitted to *AIUM*, 2015.

V. G. Halldorsdottir, J. K. Dave, J. R. Eisenbrey, P. Machado, H. J. Zhao, J. B. Liu, D. A. Merton, F. Forsberg. Subharmonic aided pressure estimation for monitoring interstitial fluid pressure in tumors: in vitro and in vivo proof of concept. *Ultrasonics*, vol. 54, no. 7, pp. 1938 – 1944, 2014.

J. R. Eisenbrey, A. Sridharan, J. B. Liu, F. Forsberg. Recent experiences and advances in contrast-enhanced subharmonic ultrasound. Accepted for publication in *Biomed Res Int*, 2014.

### *Presentations*

- |                          |  |
|--------------------------|--|
| October 3 – 4, 2013      | 28 <sup>th</sup> Annual Advances in Contrast Ultrasound & ICUS Bubble Conference, Chicago, IL, USA. <ul style="list-style-type: none"><li>• Monitoring interstitial fluid pressure in breast cancer with subharmonics.</li></ul> |
| March 19, 2014           | Biology of Breast Cancer program meeting, Kimmel Cancer Center, Thomas Jefferson University, Philadelphia, PA, USA. <ul style="list-style-type: none"><li>• Ultrasound imaging in breast cancer research.</li></ul>              |
| March 29 - April 2, 2014 | The 58 <sup>th</sup> Annual Convention of the American Institute of Ultrasound in Medicine, Las Vegas, NV, USA. <ul style="list-style-type: none"><li>• Subharmonic pressure measurements in human clinical trials.</li></ul>    |
| April 18-20, 2014        | The 2014 Chinese Congress of Ultrasound in Medicion (CCUM), Beijing, P. R. China. <ul style="list-style-type: none"><li>• Subharmonic imaging and pressure estimation: pre-clinical and clinical experiences.</li></ul>          |
| April 24 - 27, 2014      | 2014 Westlake International Forum on Ultrasound in Medicine and Biology, Hangzhou, P. R. China.  |

- Subharmonic imaging and pressure estimation: pre-clinical and clinical experiences.

May 13 – 15, 2014

The Leading Edge in Diagnostic Ultrasound, Atlantic City, NJ, USA.

- Subharmonic pressure estimation for monitoring neoadjuvant chemotherapy.

## 8 CONCLUSIONS

The development and implementation of 3D SHI and SHAPE software on the Logiq 9 scanner has been completed. However, the efforts required to obtain approvals for both animal and human trials were markedly more cumbersome than envisaged in the original submission. Nonetheless, the necessary paperwork was completed after 16 months and we started the human clinical trial in May of 2014. To date 4 subjects have been enrolled.

In summary, tasks 1 and 2 has been completed, while task 3 is ongoing, but due to the delay caused by the efforts required to obtain regulatory approval for the animal and human clinical trials, the project is approximately 12 months behind schedule and we, therefore, requested - and were granted - a one year no cost extension.

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## Appendix I

The Statement of Work from the original proposal:

### Objective 1

**Task 1:** Design and implementation of SHAPE on a commercial US scanner (months 1 - 4)

- a. Optimize 3D SHI and SHAPE based on the parameters associated with the designated transducer; the 4D10L (month 1).
- b. Modify a state-of-the-art US imaging system (the Logiq 9) to perform 3D SHAPE (since the 3D SHI contrast imaging modality was already incorporated on this system as part of R01 CA140338; months 1 - 3).
- c. Evaluate the 3D SHI imaging modality and 3D SHAPE in an *in vitro* flow phantom using the modified US scanner (month 3).
- d. Prepare regulatory submissions for clinical studies and obtain institutional approval for animal studies (month 2 - 4).

### Objective 2

**Task 2:** Optimize and calibrate *in vivo* 3D SHI and SHAPE in animals (months 4 – 5)

- a. Calibrate *in vivo* 3D SHAPE results based on pressure measurements obtained with a manometer-tipped pressure catheter (as the reference standard) in 3 mongrel dogs (months 4 - 5).
- b. Evaluate the ability of 3D SHI to depict macro- and micro-vascularity (the latter as a model for tumor angiogenesis) in the kidneys of 3 canines (months 4 - 5).

### Objectives 3 - 4

**Task 3:** Conduct human clinical trial, data collection and analysis (months 5 - 24)

- a. Validate the clinical potential of 3D SHI as a tool to monitor neoadjuvant chemotherapy (i.e., the ability to track changes in tumor angiogenesis) in women with LABC by studying 20 – 50 subjects before as well as after the 1<sup>st</sup>, 3<sup>rd</sup> and last chemotherapy cycle and comparing results to MRI and pathology findings (months 5 - 23).
- b. Validate the clinical potential of 3D SHAPE as a tool to monitor neoadjuvant chemotherapy (i.e., the ability to track changes in IFP) in women with LABC by studying 20 – 50 subjects before as well as after the 1<sup>st</sup>, 3<sup>rd</sup> and last chemotherapy cycle and comparing results to MRI and pathology (months 5 - 23).
- c. Evaluate the ability of 3D SHI to depict LABC neovascularity in women compared to CD31 stained specimens (Months 5 - 23).
- d. Perform statistical analyses and write final report (months 23 - 24).